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13. ABSTRACT (Maximum 200 words)

Tristan Technologies, Inc. is working to apply SQUID magnetometry to problems in nondestructive evaluation which are important to the Strategic Defense Initiative. We have designed and are nearing completion of an innovative Non destructive Evaluation (NDE) instrument that, unlike most existing instruments, can be used for studying deep sources with applied fields. We will assess the effectiveness of this SQUID NDE system for a broad range of nondestructive evaluation problems related to high-performance aircraft bearings, nuclear reactor fuel tubes, titanium billets for aircraft turbine blades, high-temperature superconducting magnetic shields, and riveted joints in military and commercial aircraft. In various applications, SQUID magnetometers could facilitate the development of high-performance devices, reduce manufacturing costs, monitor performance and assure quality control in manufacturing, and help prevent catastrophic failures of aircraft, satellites, weapons and other military systems. During Phase III we will design and commercialize instruments specifically to meet the most promising NDE applications for SQUID magnetometers.

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1. Work Statement

The statement of work for this project is as follows:

I. Build a 5 channel SQUID-based NDE instrument that can be used for studying deep sources. It will comprise the following elements:

> -- 5-Channel SQUID magnetometer probe with four, 5mm diameter, 1st derivative axial pickup coils and one, 25mm diameter, planar, concentric gradiometer.
>
> --Liquid helium Dewar for use with the magnetometer probe and having a 5mm spacing between the outer Dewar wall and the pickup coils.
>
> --Superconducting magnet assembly on the probe capable of applying a 500 gauss D.C. field and 1 gauss A.C. field at a point 1 cm below the Dewar.
>
> --Noise reduction circuit to cancel the applied A.C. field that is directly coupled to the magnetometer.
>
> --Computerized data acquisition and control system to operate the SQUIDS, magnet assembly, and noise reduction circuit. Custom software will be written to perform these control functions, collect the data and analyze it to perform the experiments listed below.

II. Use the 5-channel system to perform the following studies:

> --Identification of Flaws, Regions of Local Stress, and Precursors to Plastic Flow in Ferromagnetic Components.
>
> --Clarify the microscopic mechanism responsible for the magnetic precursor to plastic flow in ferromagnetic materials.
>
> --Determine how the magnetic precursor correlates with Barkhausen noise.
>
> --Demonstrate the multiple-channel SQUIDs can localize the sites in the sample where individual stress-induced Barkhausen jumps are occurring.

III. Detection of Subsurface Flaws and Cracks, Such as Rolling Crack in Bearings for high-performance Aircraft.

> --Determine whether high-resolution SQUID magnetometry can detect a precursor to either crack formation or the subsequent spallation from rolling contract in cylindrical test samples.
>
> --Determine whether high-resolution SQUID magnetometry can allow nondestructive, quantitative observation of subsurface cracks, so that the factors governing the generation and growth of these cracks can be more readily determined.

2. Significant Accomplishments and Progress

During the first year of this contract, the NDE system was designed and fabrication is near completion and is on schedule.

As currently implemented, this system significantly exceeds the capabilities that were originally proposed. This is because we were able to identify several other companies that have an interest in applications of the type of equipment being constructed for the SBIR. They, in turn, specified and funded enhancements. These enhancements were then included in the NDE system at no cost to the program.

We have already shipped three systems that incorporate this technology and have orders to ship three more.

Some industrial applications that have assisted us in system enhancements include:

A manufacturer of Nuclear Fuel Rods.

A program with Vanderbilt University that is funded by a large U.S. company.

A two year development program with a large Steel manufacturer.

Most of the enhancements were in the area of analysis software and noise reduction techniques.

In the coming year, we expect to use the NDE system to complete the studies identified in the Statement of Work. These studies will begin within the next four months and, based on accomplishments to date, we have every expectation that they will be completed on schedule.

2.1. Progress and Status.

The current status of the 5 channel SQUID-based NDE instrument is as follows:

5- Channel SQUID magnetometer probe.
Construction of the probe assembly is nearing completion. Most machined components have been produced and assembled. We have solved the problems associated with making persistence switches and magnets. We have also solved EMI problems in the SQUID feedback circuits. We are currently involved in a study of coil types with diameters ranging from 0.3cm to 1cm.

Liquid Helium Dewar
The Dewar has been fabricated and tested.

Superconducting magnet assembly.
Design of the magnet assembly is complete. Construction partially complete.

Noise reduction circuit.
The noise canceling unit (NCU) has been completed and is operational.

Computerized data acquisition and control system.
Software has been developed and is now capable of acquisition and control of up to 8 SQUID channels with up to 8,000 data points per block. Maximum acquisition rate is 250Hz. Graphics capabilities include generation of 3D and 2D plots of a scanned surface.

The Scanner table subsystem has been constructed and is working properly.

2.2. System Description

The main components of the system are:

- Five-Channel SQUID Magnetometer Probe
- Liquid Helium Dewar
- D.C. and A.C. Magnet System
- A.C. Nulling System
- Computer Control and Data Acquisition System

These components are connected to form the NDE system as shown in Figure 1.

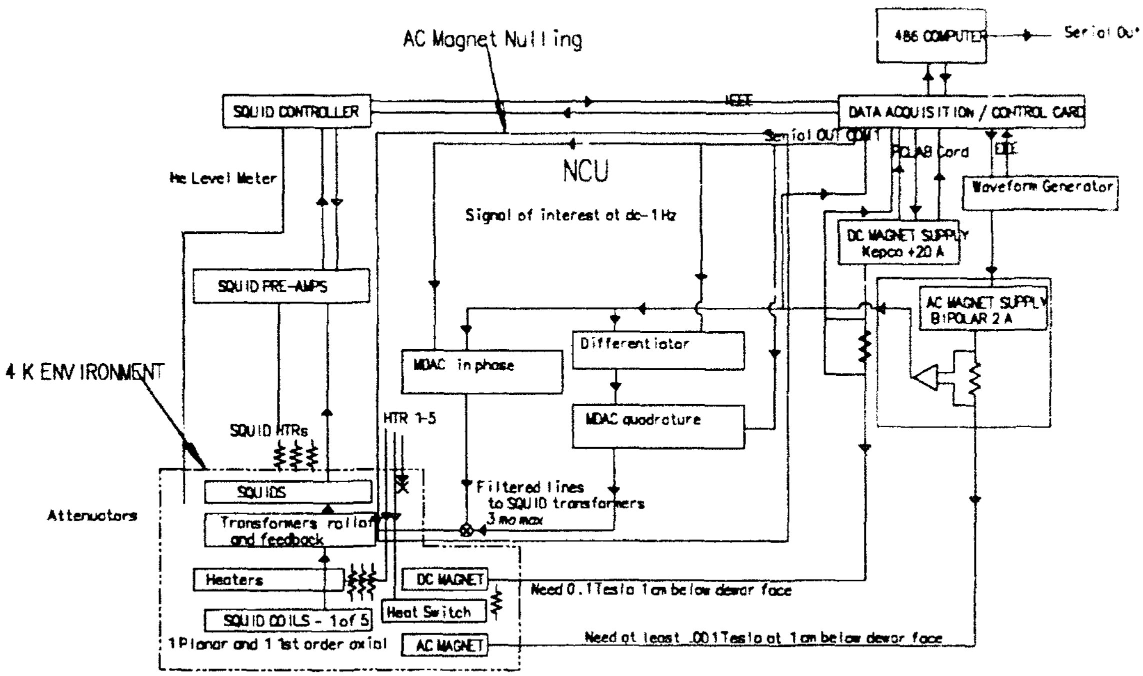


Figure 1: System block diagram

2.2.1. Five Channel SQUID Magnetometer Probe

An engineering drawing of the Magnetometer Probe is shown in Figure 2.

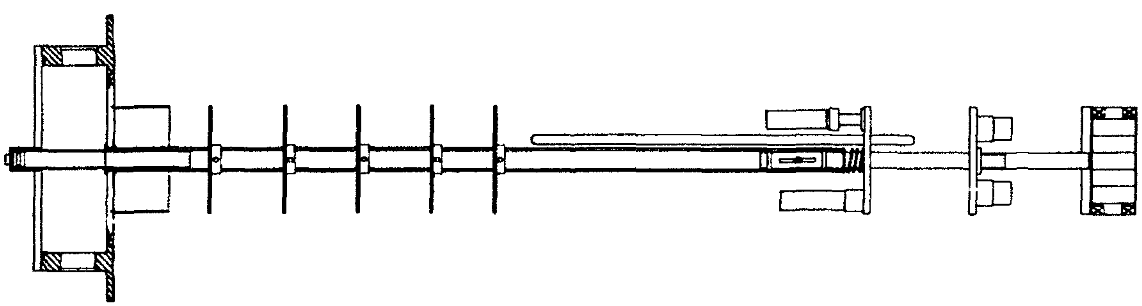


Figure 2: Magnetometer Probe Drawing

The SQUID input coils are constructed entirely of low temperature superconducting materials. The entire input loop is superconducting with a rolloff of about 1 KHz. The inputs have a spatial sensitivity as shown below in Figures 3 and 4.

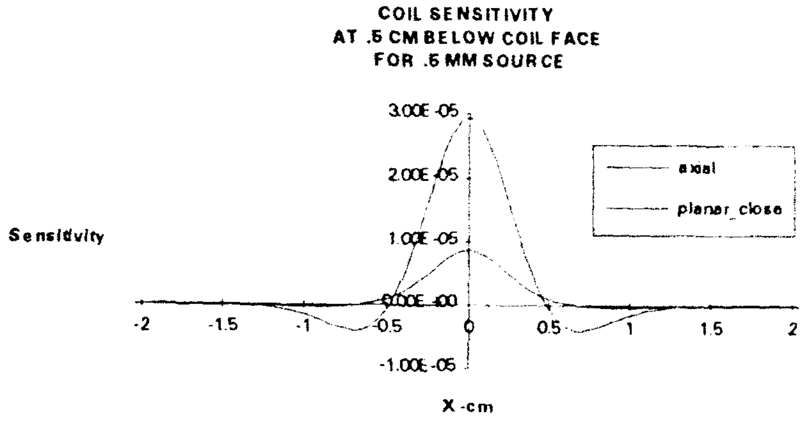


Figure 3: Detector Coil Sensitivity 0.5 cm below coil face.

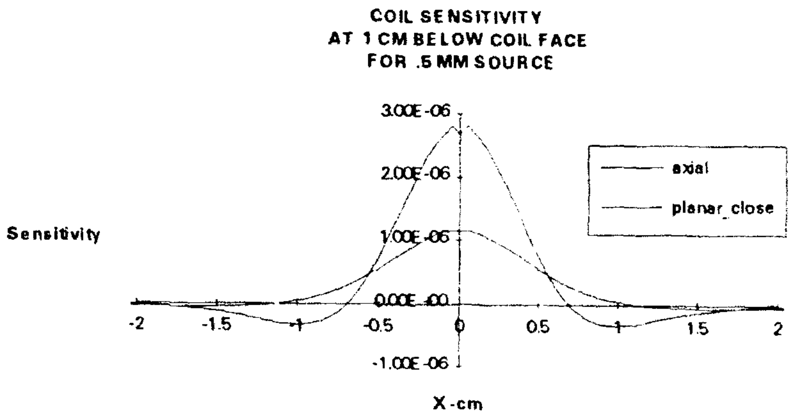
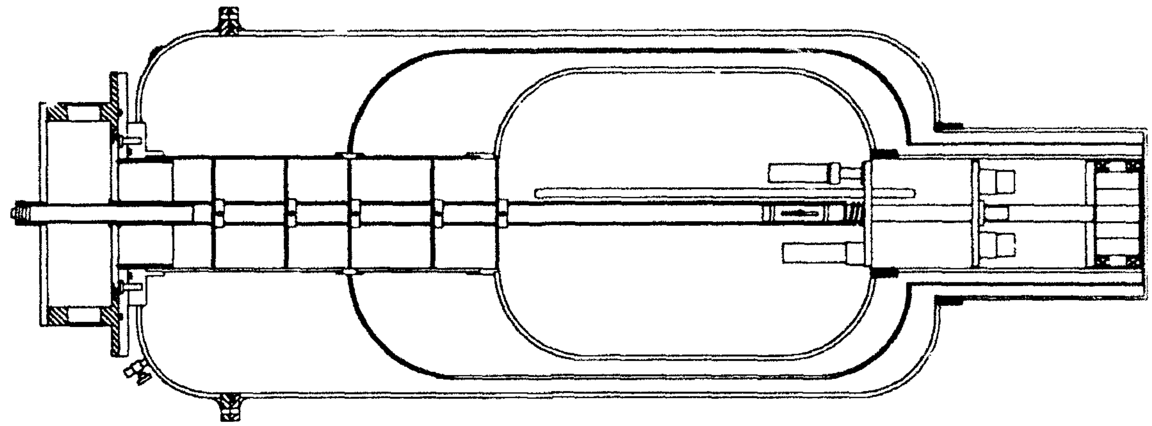


Figure 4: Detector Coil Sensitivity 1.0 cm below coil face.

2.2.2. Liquid Helium Dewar

An engineering sketch of the Liquid Helium Dewar that has been fabricated to hold the magnetometer probe is shown in Figure 5.



SBIR 2007-001

Figure 5: Liquid Helium Dewar

2.2.3. D.C. and A.C. Magnet System

D.C. Field System

The superconducting magnet on the magnetometer probe will be capable of applying a 0.2 Tesla D.C. magnetic field to a sample located below the bottom of the Dewar. The D.C. magnet operates in a persistent field mode.

Power supplies are provided to operate both the magnet current and persistent switch heater. The switch heater, D.C. current amplitude, and ramp rate are all controllable from the computer. (The operator may be required to turn the power on to the D.C. supply prior to changing the field and the software will warn the user as necessary).

The D.C. magnet is 2.4 cm in diameter and 0.9 cm long. The measured field profile from this magnet is shown in Figure 6.

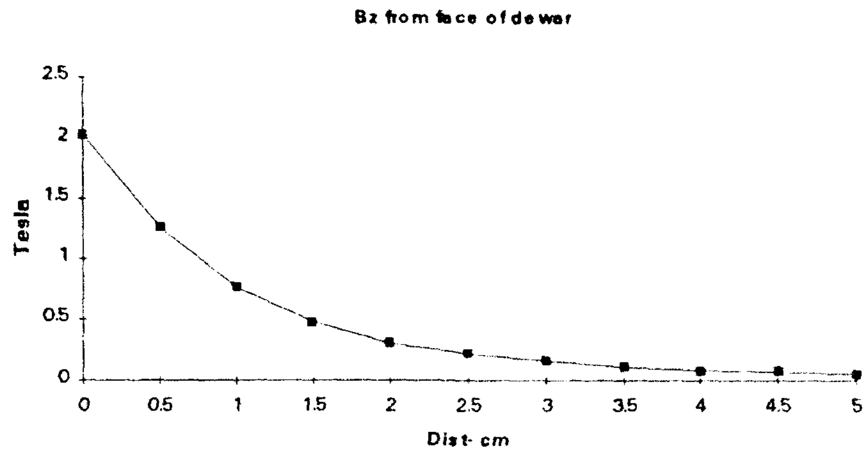


Figure 6: Magnetic Field as a function of distance along the axis.

A.C. Field

An A.C. field of amplitude 0.0002 Tesla below the bottom of the Dewar may be produced. This magnet will be operated in the persistent mode to maintain the D.C. field simultaneously with the A.C. field; the A.C. field will be produced by inductive coupling of flux into the magnet circuit. The circuit is shown in Figure 7. A power supply is provided to generate the A.C. field under computer control. The amplitude and frequency of the A.C. field is adjustable using the computer control system.

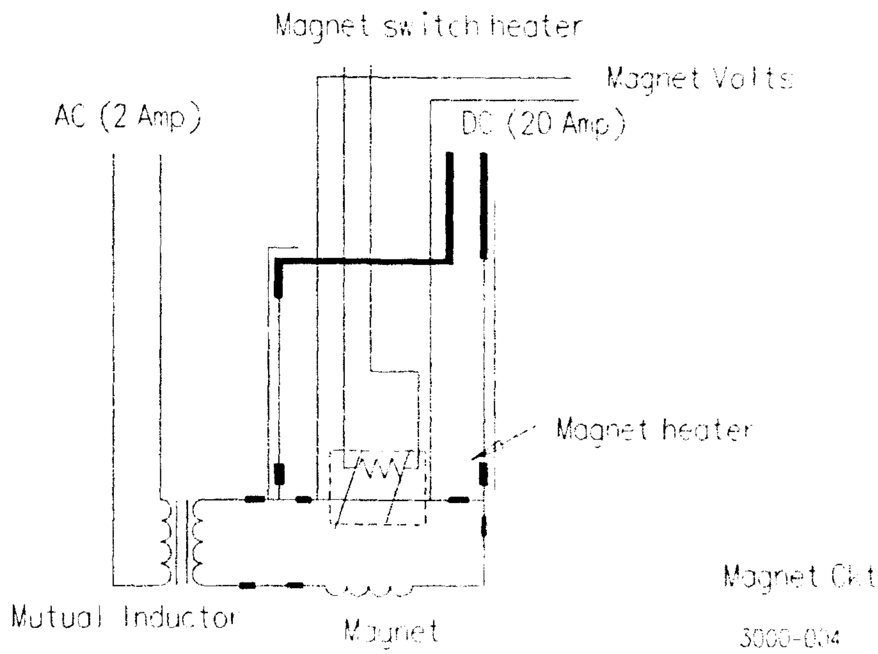


Figure 7: Superconducting magnetic field circuit.

2.2.4. A.C. Nulling System

A custom designed A.C. nulling circuit will supplied in order to cancel A.C. flux from the A.C. magnet that is coupled into the input circuits. This circuit is shown schematically in Figure 8.

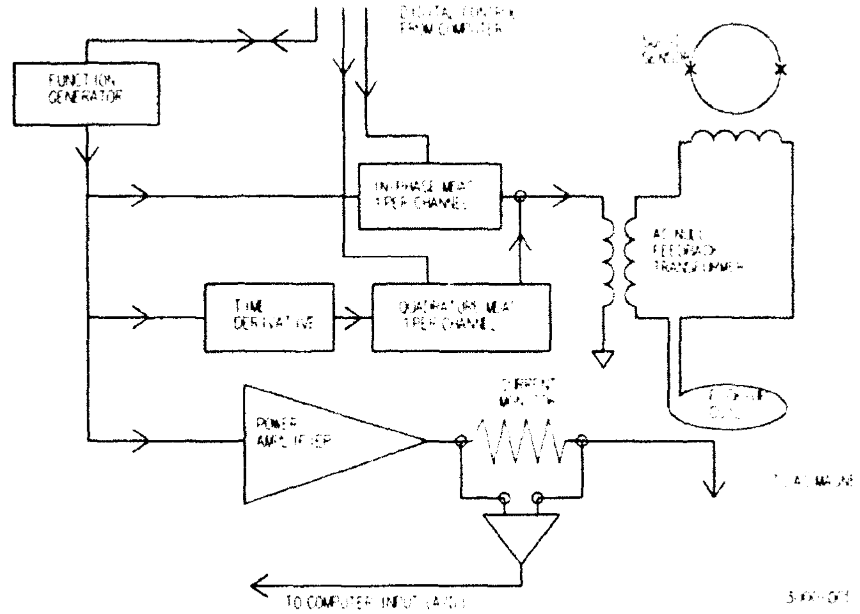


Figure 8: A.C. Nulling block diagram.

Since the gradiometers can not be perfectly balanced, a large A.C. signal will be directly coupled into the system whenever the A.C. magnet is used. Even if the magnetometers are perfectly designed and manufactured, a large A.C. signal would still be directly coupled to the pick up coils due to the radial gradient of the applied A.C. field. Although we could design the coils to reject this gradient, the coils would then not work so well to reject other magnetic noise. Furthermore, placing a metal object under the magnetometer would seriously degrade this rejection capability.

The directly coupled A.C. flux detected by the gradiometer is between 1% and 5% of the flux that would be detected by a magnetometer of the same size. This results in an extremely large A.C. signal which is independent of the sample. In most cases, this signal will be so large that it will be nearly impossible to analyze the data to detect flaws.

With a carbon steel sample under the system, we expect that the A.C. flux detected by the gradiometer will many times larger than the signal which would be detected by a magnetometer if no sample were present. The dynamic range of the data acquisition system will not be adequate to track this large signal while still resolving the small signal from defects in the metal.

To minimize this problem, we will require an A.C. magnet nulling system. This system consists of the following items:

- Special circuitry to generate in-phase and quadrature feedback signals to null the A.C. signal in the SQUID. This circuitry will receive an analog input from the magnet power supply and digital input from the computer. The computer input will adjust the amplitude of the in-phase and quadrature signal used to separately null the A.C. signal on all SQUID magnetometer channels.

- All necessary modifications to the magnetometer probe and SQUID electronics allow injection of the A.C. null signal directly into the input circuit.

- Software to automatically optimize the feedback signal. When the operator issues a single command, the computer will automatically analyze the data from the magnetometer and feed back the appropriate signals to null the A.C. output. Software will allow manual adjustment of this null.

This system is capable to null A.C. signals of any amplitude up to the full scale ± 5 Volts p-p output of the SQUID magnetometers when operated on range x500. The nulling circuit has at least 12 bits of resolution which will result in a maximum A.C. output after null of less than 2 mV rms for a full scale output from the SQUID magnetometer.

Provision is made to switch the full scale feedback signal to be 10 times the full output of the magnetometers. This allows the operator to adjust the null signal with a low level A.C. field and then turn up the A.C. field amplitude signal to an amplitude which would otherwise have caused an overload of the SQUID.

We expect that the quadrature null will usually be used when applying A.C. magnetic fields to conductors. With this A.C. MAGNET NULLING option, it will be possible to null the magnetometer output after placing the sample under the system. Any defects in the test sample will then show up as large changes in the A.C. output of the system as the sample is scanned under the magnetometer. Since the null can be set quickly and automatically by computer, we expect that it should be done every time a new sample is placed under the magnetometer.

Noise Cancellation Unit (NCU)

The Noise Cancellation Unit has been fabricated by Tristan Technologies, Inc. and includes the room temperature electronic circuits required to perform the A.C. magnet nulling function. It also provides miscellaneous other circuits such as: 1) Relays to turn SQUID heaters on or off, 2)control relays for various switching applications, and an A.C. magnet current output. The major sections of the circuit are shown in block diagram below.

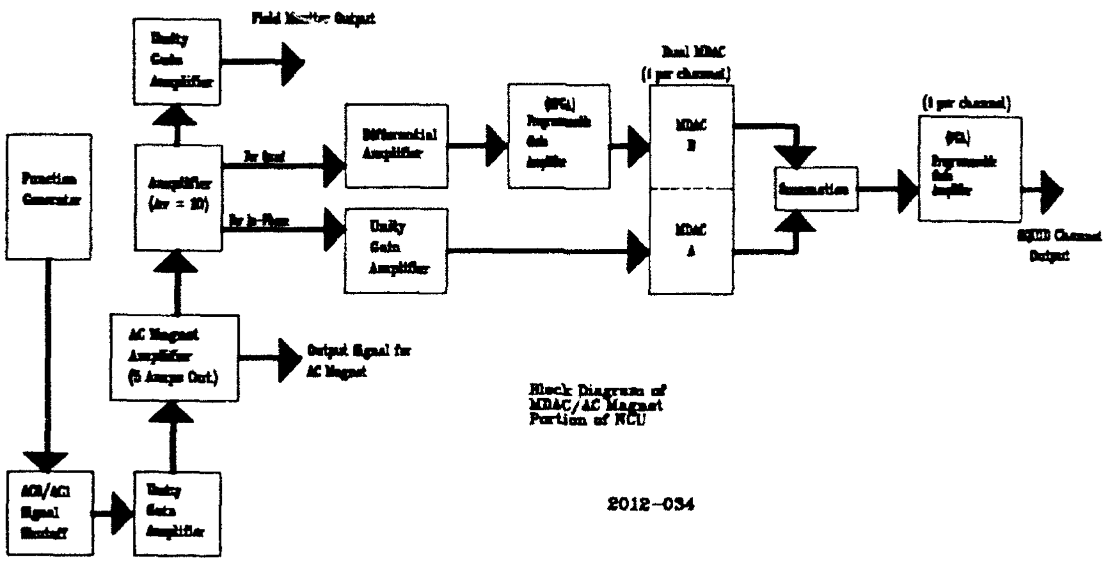


Figure 9: NCU MDAC/A.C. magnet Block Diagram

2.2.5. Computer Control and Data Acquisition

All of the system Data Acquisition electronics and the computer control system will be housed in a custom-fabricated control console. This console is desk-like in nature and will be approximately 1.5 m wide by 0.6 m deep by 0.7 m tall. A single power cable from this console provides A.C. mains power to all necessary components in this system.

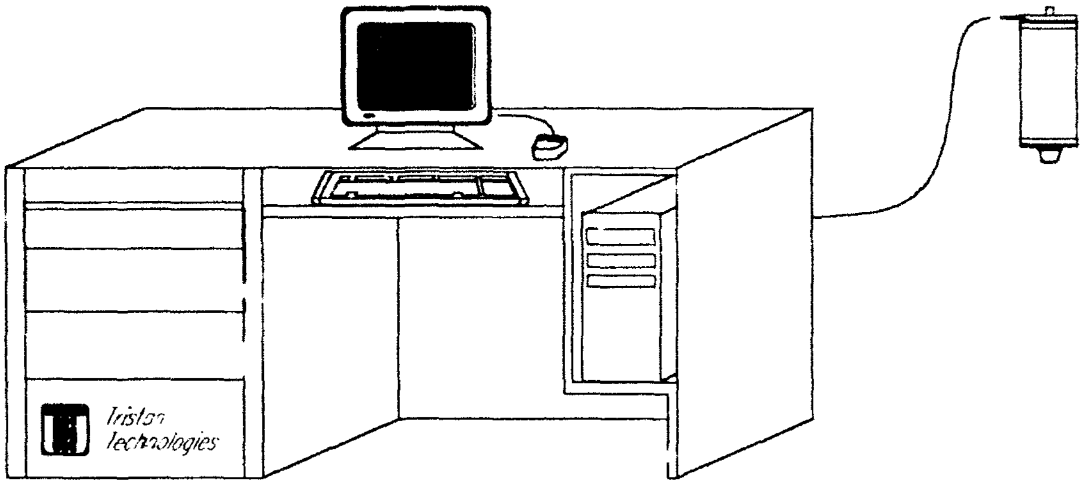


Figure 10: Superconducting magnetic field circuit.

The NDE system is controlled by an IBM-AT compatible computer system mounted within the control console. This equipment includes:

- 80486 microprocessor
- Color monitor
- Mouse and keyboard
- 4 MByte memory
- 200MByte hard disk
- One 5.25" floppy (1.2 MByte)
- One 3.5" floppy (1.44 MByte)
- Combination Analog and Digital I/O card.
- IEEE-488 compatible digital communication card
- Two, RS-232 communication ports
- One, Centronics compatible, 8 bit parallel port
- One, cartridge tape back up (120 MByte compressed capacity)
- MS DOS 5.0 operating system
- National Instruments Lab Windows Software

Software is being developed that will perform data acquisition from all SQUID channels, control of all system components, and analyzing the data to determine the magnetic properties of the sample being tested.

Some specific features include:

A.C. Field Control
Both amplitude and frequency of the sinusoidal, A.C. field applied to the sample are computer controlled. The field is automatically turned on and off as required during specific measurements.

D.C. Field Control
The D.C. field amplitude and ramp rate is computer controlled. A fully automated routine operates the heat switches and ramps the field as required.

SQUID Control
All necessary functions of the SQUID system are under computer control via the IEEE-488 bus. Utilities is provided to allow direct operator control of:

- SQUID Gain
- SQUID Reset
- Range
- SQUID Heaters

These, and many other SQUID control functions, are automatically controlled as required to perform various sample measurements. In particular, all necessary data acquisition parameters are automatically set by the computer prior to a sample measurement.

Heater Control
The magnet persistent switch heater, SQUID heater, and pick up coil heaters are operable from the computer console. These heaters are also automatically switched on and off as required for various sample measurement procedures.

Interface to Automated Motion Control
The system is capable of interfacing to an automated magnetometer positioning mechanism. Communication between the positioning mechanism and the data acquisition computer will coordinate the motion to the acquisition of data.

AC Signal Nulling
Complete control of the A.C. Field Nulling Circuit allows the operator to manually null the in-phase and quadrature signal from the A.C. magnet that is detected by each SQUID channel. An automated procedure is also supplied that automatically nulls the signal from all channels by issuing a single command prior to data acquisition.

Automated Data Acquisition Procedures
Three classes of automated data acquisition procedures are planned:

- Manual Trigger Mode; where the operator will trigger each burst of data using the computer mouse.

- Timed Mode; where each burst of data will begin after a predetermined delay time until all bursts specified have been acquired.

- Remote Trigger Mode where each burst of data will be triggered by a remote signal. This will usually be used to synchronize data Acquisition with the scanning device.

In each mode, the operator is prompted to specify:

- Channels from which data is to be acquired.
- Data acquisition rate (samples/sec).
- Number of data points to be acquired in a single burst.
- AC field amplitude and frequency.

If the operator desires, and the acquisition rate is slow enough to allow for it, the operator will be able to view the acquired data in real time on the CRT monitor.

Data Analysis Functions
After the data has been acquired and stored in a file, the operator is able to process the data using a variety of data analysis functions.

All data that is acquired is stored in a standard format that will include a header file describing all of the important data acquisition parameters. A new file will be created by the data analysis function that has the same format as the original file. The header file will be modified to indicate that the data has been processed by the specified data analysis function.

Several data analysis functions will be required. Currently planned functions include:

- Decimate - This reduces the number of data points stored in the file by rejecting a specified percentage of the data points. A specified number of points at the beginning and end of each data burst can also be rejected.

- FFT -A fast Fourier transform will be applied to each burst of data.

- Average - This averages the data over a specified parameter, e.g. the data from all bursts in the file could be averaged together or multiple FFT's could be averaged together.

- B/H Slope - Calculate the ratio of change in magnetometer output to change in applied field. This ratio can be calculated for each cycle of applied A.C. field or for the average of all cycles of applied field during the data burst.

- B/H Area - Calculate the area of the B/H loop. This can be done for each cycle of applied field or for the average of all cycles.

- Amplitude - Calculate the peak-to-peak amplitude of the magnetometer output (or any other measured output) during a single cycle of applied A.C. field or during a single burst of data.

- Filter - This applies a low-pass, high-pass, or band pass digital filter to the data.

Data Plotting Functions
A variety of data plotting functions will be required in order to operate on the standard data format. This will allow any data file to be plotted in any of the following formats (some of these formats may not be meaningful for some of the data files).

- Time Series - Plots the data amplitude versus data point

- X-Y Plot - Plots the amplitude of one magnetometer function versus A.C. current.

- Contour Plot - Plots the amplitude as a contour plot versus X-Y position.

- 3-D Contour Plot - Plots the amplitude of a data set versus X-Y position.

3. Publications

4. Professional Personnel Associated with the Research Effort

Dr. Douglas Paulson, Principal Investigator
Ph.D. Physics, University of California at San Diego, 1974.
Dr. Paulson has designed and developed many SQUID-based magnetometer systems and applied them to a wide variety of research topics for more than 25 years.

Dr. Duane Crum
Ph.D. Physics, The Ohio State University 1973
Dr. Crum has managed the design, development, and use of SQUID magnetometers for applications in NDE, geophysics, biomagnetism, physics, and chemistry. Most recently, he was the principal investigator on an EPRI funded grant to use SQUID magnetometers for NDE of metal objects. Many of the techniques and measurement problems are similar to those encountered on this project.

Guy Covert
M.Sc. Electrical Engineering, California State University, San Diego, 1972
Mr. Covert has over 22 years experience in electronic design and software development including analog circuit design, microprocessor systems, CAD equipment design, and digital signal processing system design.

Dr. Raymond Sarwinski
Ph.D. Physics, University of Illinois, 1966
Dr. Sarwinski has over 30 years of experience in the design of advanced cryogenic systems for applications in the military and commercial sectors. His specialties are magnet design, magnetometer design, theoretical analysis, ultra-high sensitive instrumentation, and the design of closed-cycle refrigeration systems.

John Peter Wikswo, Jr.
MOS. and Ph.D. - Physics, Stanford University, 1973
Appointments
Research Fellow in Cardiology, Stanford University School of Medicine 1975-1977
Assistant Professor of Physics, Vanderbilt University 1977-1982
Associate Professor of Physics, Vanderbilt University 1982-1988
Professor of Physics, Vanderbilt University 1988-AMB. Learned Professor of Living State Physics (effective September 1991)

5. Interactions

The Foster Miller Company.
The Foster-Miller Company is expert in the areas of aircraft and nuclear power plant NDE. We have worked with them during the past year to prepare and submit two proposals to the U.S. Air Force.

It is our plan to work with Foster Miller during the coming year to find additional aircraft NDE applications. To accomplish this, Tristan Technologies, Inc., or the Foster Miller Co. will identify and contact the civilian and military personnel responsible for NDE of most of the major aircraft in the Air Force fleet. These conversations will provide the data base from which a list of applications can be generated. Some of the individuals that have, or will be, contacted include:

- Steve Baughman — Lockheed, Marietta, GA — (C-141 and C-5A)
- T. M. Cordell — Wright Patterson AFB, Branch Chief, NDE Branch, Materials Directorate, Wright Lab.
- Richard Kinsey — Air Force Corrosion Program, Warner Robins AFB
- Donald Hazen — Warner Robins Air Logistics Center
- David Raulerson — Pratt and Whitney
- Various personnel — McDonnel Douglas — (F-15)
- Crawford Battle — F-15 Program Depot Maintenance, Warner-Robbins AFB
- Dean Bolton & Staff — Sacramento Air Logistics Center, McClellan AFB
- Leon Yeager — Hill AFB — (F-4)
- Capt. Bullock — Hill AFB — (F-16)
- Hugh Nelson — Warner Robbins AFB — (C-130)
- Clarence Hitchings — San Antonio Air Logistics Center — (C-5)

All of the personnel who have been contacted thus far have indicated a willingness to provide additional information in support of this effort.

6. New Discoveries, Inventions, Patent Disclosures and Applications.

None identified or applied for as yet.

7. Additional Statements

None.